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Scaling Down of PWR Nuclear Power Plant Secondary Side Conditions for SIRIO Experimental Facility Supported by System Thermal-Hydraulic Codes

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ABSTRACT

The concept of the Passive Isolation Condenser (PIC) in which an ingress of non-condensable gas may reduce the steam condensation rate, is described. The scaling down from Pressurized Water Reactor (PWR) operating conditions to experimental conditions of the SIRIO facility is presented. The simulations of the planned experiment with the system thermal-hydraulic codes RELAP5 and TRACE indicate, that the experiment should confirm the applicability of the proposed PIC concept for PWR technology.

1 INTRODUCTION

One of the major issues in nuclear safety is that experimental facilities are much smaller (usually at least by an order of magnitude) than the actual systems on which the experiments are supposed to provide information. For this reason, conditions in actual nuclear power plants (NPPs) have to be adequately scaled-down to the size of experimental facilities.

Within the European project PIACE, a concept of Passive Isolation Condenser (PIC), in which the heat removal from the reactor core is slowed down by decreasing the steam condensation rate using injection of a non-condensable gas, has been proposed [1]. In a Pressurized Water Reactor (PWR), the condenser should be connected to the steam generator secondary side.

The suitability of the concept will be verified in the SIRIO experimental facility [2, 3] that will represent the PIC. As the facility is much smaller that the PIC projected for an actual NPP, flow conditions have to be suitably scaled-down. After that, performing simulations of the planned experiment may provide an indication of the expected outcome at relatively low cost (both in the sense of effort and expenses). Namely, although the results of the simulations are not expected to provide necessarily the same results (within uncertainty limits) as the results of the planned experiment, they might still be expected to support the adequacy of the prescribed scaled-down initial and boundary conditions.

In the present paper, the scaling down of plant accident conditions and the simulations of the planned experiment are described.

2 PASSIVE ISOLATION CONDENSER

The proposed concept of the Passive Isolation Condenser (PIC) is shown in Figure 1. Basically, steam from the steam generator (SG) secondary side flows into the isolation condenser, where it condenses, causing pressure and temperature decrease on the SG secondary side and contributing to decay heat removal from the reactor core during an accident. The introduced innovative concept is that the condenser lower head is connected to a tank of non-condensable gas. When the pressure in the condenser lower plenum drops below a certain value, the non-condensable gas should flow into the condenser tubes, thus reducing the condensation rate. This in turn should lower the pressure and temperature decrease rate and reduce the cooling rate of the reactor core. While the benefits may be different for different technologies, for PWR technology the rationale is that the limitation of the core cooling rate will prevent high thermal stresses due to fast temperature decreases.

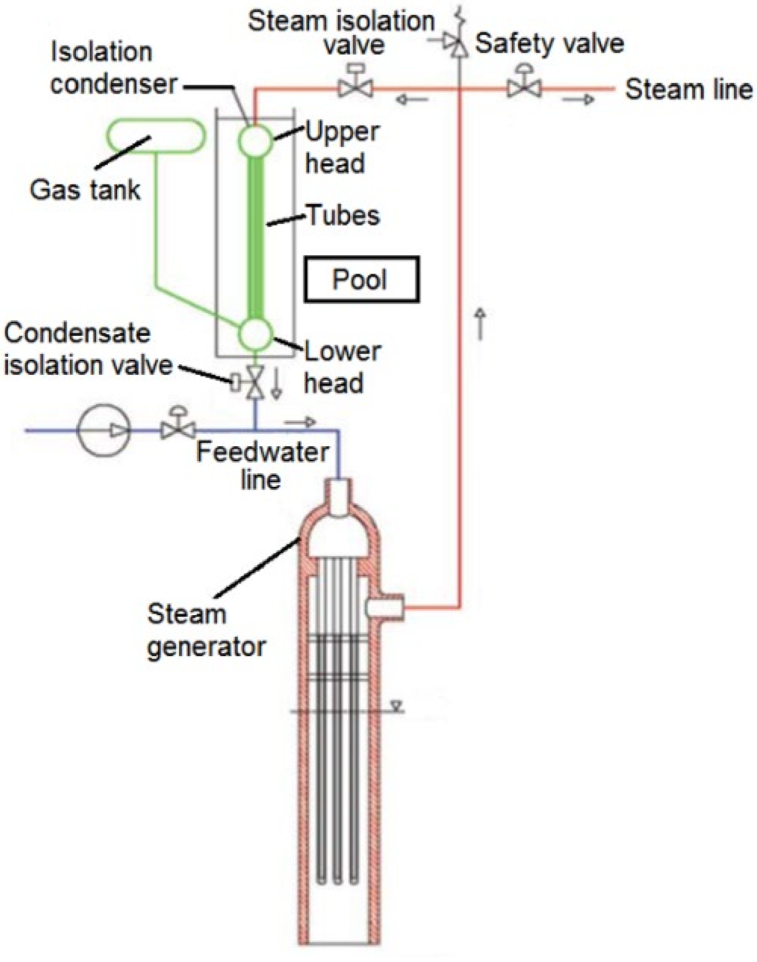

Figure 1. Schematic of Passive Isolation Condenser.

3 SIRIO EXPERIMENTAL FACILITY

The SIRIO experimental facility is located at the SIET company in Piacenza (Italy). The basic principle of the facility is shown in Figure 2. Two loops may be created by opening/closing valves: a loop with a heat exchanger, to establish a steady state, and a loop with the condenser (that is, the PIC), to replicate the steam condensation and subsequent cooling, limited by the ingress of the non-condensable gas, that takes place in the proposed design. The steam generator is represented by electrical heating of salt in a bayonet arrangement, which in turn heats and evaporates liquid water.

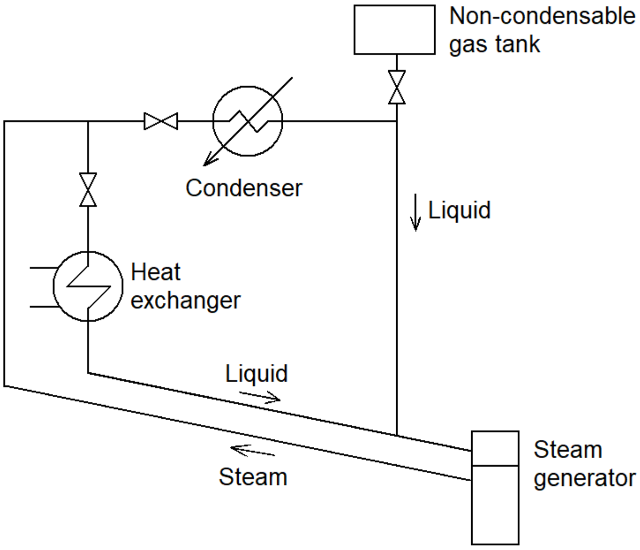

Figure 2. Principle of SIRIO experimental facility.

4 SCALING DOWN OF PWR CONDITIONS TO EXPERIMENT CONDITIONS

To prove the suitability of the PIC concept for PWR, an experiment in the SIRIO facility is planned. However, the power of the steam generator of the facility, 55 kW, is several orders of magnitude lower than the power to be removed from the SG secondary side. Thus, the PWR operating and accident conditions need to be scaled down.

Although scaling down from actual nuclear systems to experimental conditions is fairly common, so far there are no established universal principles and methodologies. Mostly, ad-hoc procedures are applied. The specificity of the present scaling is that the geometrical characteristics of the experimental facility are already defined. Therefore, the scaling-down should be done mostly in terms of experimental conditions, with eventually some minor modifications of the facility.

The SIRIO parameters in the simulations, described in the documentation [3], are:

- SG inlet temperature: ~335 °C (P_{sat} = 137.1 bar)
- Pressure: 180 bar (t_{sat} = 356.5 °C)
- Power: 55 kW

The following rules were adopted for the initial scaling-down (although pre-test simulations may then lead to somewhat different values than first estimations).

1st rule. The initial pressure in the SIRIO facility should not be much higher than the pressure in the performed simulations for the PWR. The selected initial value will be 60 bar (t_{sat} = 275.6 °C) in the SG. This rule was set so that the pressure in the experiment is in accordance with the pressure in the simulated transient.

2nd rule. The mass flow rate in the SIRIO facility should be in the same range as in the simulated steady state, described in the documentation [3] (that is, between 20 g/s and 80 g/s). This rule was set so that the mass flow rate during the experiment is in the same range as assumed in already performed simulations.

3rd rule. The removed power in the SIRIO facility will be close to 50 kW. As the 2nd rule, this rule was also set so that the removed power during the experiment is in the same range as assumed in already performed simulations, described in [3].

In preliminary algebraic calculations [4], the heating of the liquid in the bayonet tube annulus (that represents the steam generator) from inlet subcooling conditions to saturation temperature was neglected (only heat transfer in two-phase flow was accounted for). Applying these rules, assuming the removed power in PWR to be 15 MW (which corresponds to the decay heat to be removed through one SG after some 10-15 s), the mass flow rate in the PWR was calculated (taking into account saturated conditions at 60 bar) as 9.55 kg/s. Assuming the SIRIO SG power at 50 kW, the mass flow rate in the SIRIO facility is 0.0318 kg/s.

5 MODELLING WITH RELAP5 AND TRACE CODES

To infer the probable course of the planned experiment, simulations were performed. Jozef Stefan Institute (JSI) and Universidad Politécnica de Madrid (UPM) have developed models of the SIRIO experimental facility for the RELAP5 and TRACE thermal-hydraulic system codes, respectively. Both codes have been used extensively for simulations of transients in actual NPPs. The RELAP5 model (Figure 3) was based on the model for the RELAP3D code provided by Ansaldo Nucleare [3], whereas the TRACE model (Figure 4) was adapted based on the previous UPM TRACE model developed for the SIRIO facility [5,6]. The same decay heat, initial and boundary conditions were prescribed in both models. However, due to some differences in the code concepts, different modelling had to be adopted for some specific details.

It should be emphasized, that the purpose was not to obtain a good agreement between the results calculated by the two codes. Rather, the purpose was to prepare input models as similar as possible. However, as already stated, due to some different features of the codes, this was not possible, and may be the main reason for the observed differences between the calculated results.

In the base case, the prescribed shutdown time was 2000 s. This is the time during which the heater (mock SG) provides 55 kW of constant heating before starting the shutdown and following the decay heat curve. Other cases with different shutdown times were also simulated, but are not described in the present work.

5.1 Heat transfer in bayonet

The main difference between the RELAP5 and TRACE models is the modelling approach of the power delivered to the system through the bayonet, representing the temperature of the molten salts. In the TRACE model, the surface temperature calculated by the logic control is prescribed inside the HS (heat structure). The RELAP5 model uses an additional loop with fluid at the corresponding temperature and configures the heat structure as a heat exchanger between this loop and the bayonet.

5.2 Heat exchanger pool level control

The heat exchanger pool level control determines the liquid mass flow to the pool; the value has to be calculated to maintain the level, considering the depletion of the liquid water due to evaporation. In the RELAP5 model, the control is done by calculating the heat added to the pool and the variation in the enthalpy between the inlet and the outlet. In the TRACE model, the same control causes instabilities, which do not allow stabilising of the pressure at the indicated point (60 bar). With the objective of mitigating this effect, the TRACE control is based on calculating the mass that the model needs to maintain the level at 50 %.

5.3 Pipe heat losses

One of the more relevant changes in the original TRACE model is the upgrade of the pipe heat losses. In the beginning, the model only considered steel and, to get the correct values of the heat losses, the heat transfer coefficient (HTC) was adapted to take into account also the rockwool insulation and set as 1.28 W/m^{2}K. After revising the model and comparing it with the RELAP5 model, rockwool was included as a material part of the pipes where the heat losses are produced and the HTC was set to 15 W/m^{2}K (natural air convection) for both models.

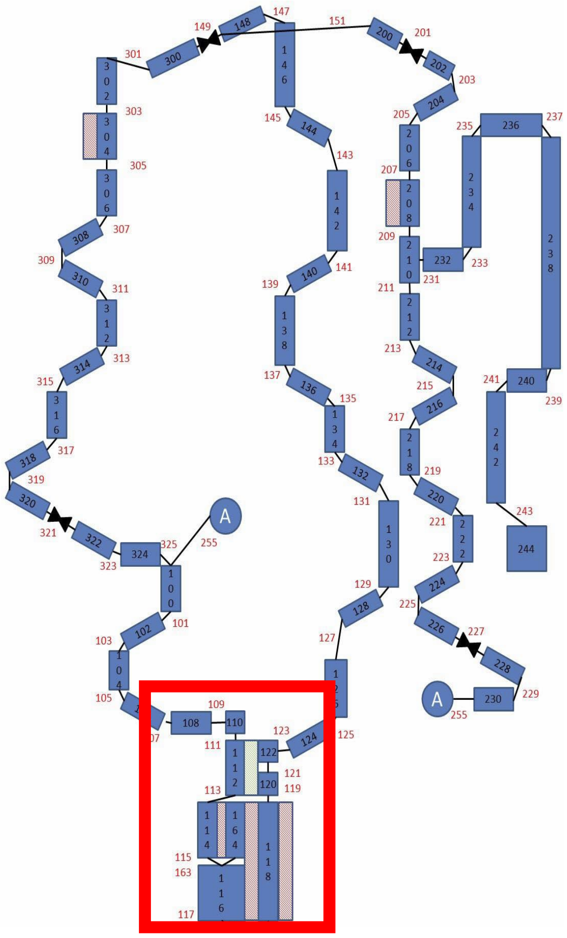

Figure 3: Input model of SIRIO facility for RELAP5 code (with indicated bayonet SG part).

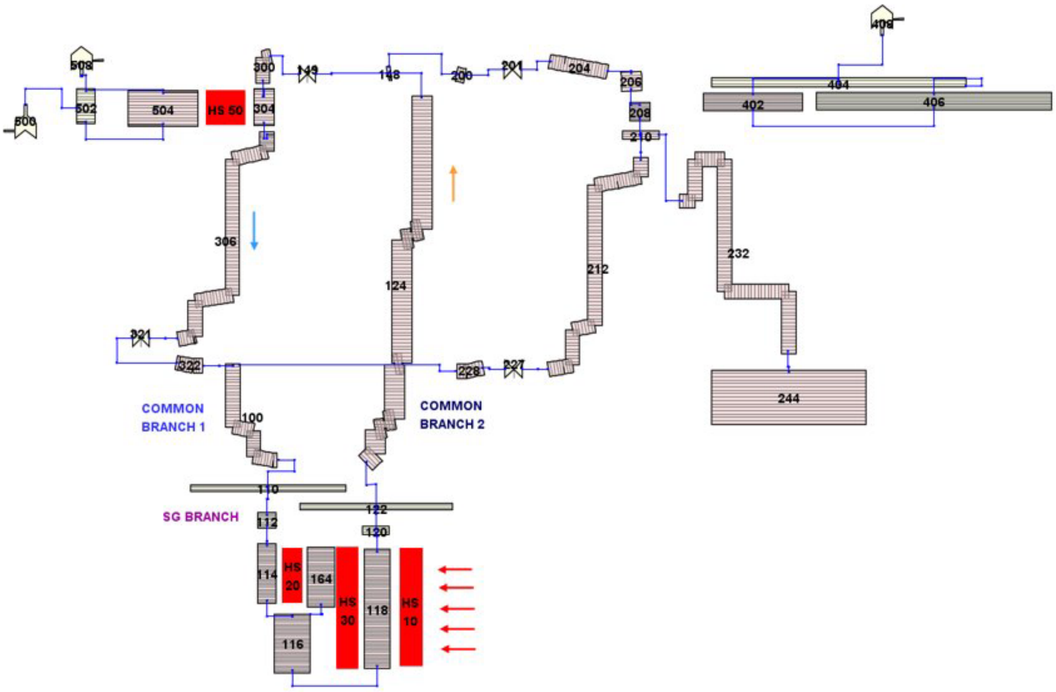

Figure 4: Input model of SIRIO facility for TRACE code.

6 SIMULATION RESULTS

6.1 Simulation of steady state

First, a steady state, where the steam flow is bypassed through a heat exchanger, with constant removed power, is established. The results of the steady state simulation are then used as initial conditions for the simulation of a transient with decreasing power.

The results, shown in Figure 5 (heat exchanger pool level), Figure 6 (pressure) and Figure 7 (salt temperature) show essentially the following:

- a steady state is indeed established;
- after initial transients, where significant differences appear (in particular, the pressure drop in the TRACE simulation at the very begining, for which no explanation was found so far), steady-state values for pressure, obtained in simulations with the RELAP5 and TRACE codes are, if not very close, still very similar; however, the temperature difference is of the order of 10 to 15 °C.

These results suggest that in the experiment, a steady state should also be established at the prescribed initial and boundary conditions.

6.2 Simulation of transient

Conditions established during the simulation of the steady state were taken as initial conditions to simulate the transient. In the transient simulation, the steam flow was directed through the PIC, with the heating power maintained at nominal value for 2000 s before applying the decreasing curve power to imitate the decay heat. The valve for the condenser line (steam isolation valve) opens when pressure upstream reaches 66 bar, but the valve located downstream of the PIC (condensate isolation valve) opens with a 30 s delay.

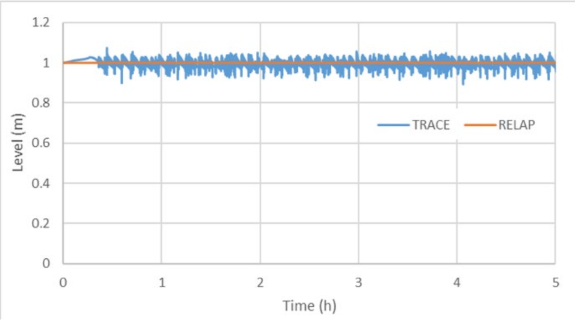

Figure 5. Level in heat exchanger pool during simulation of steady state.

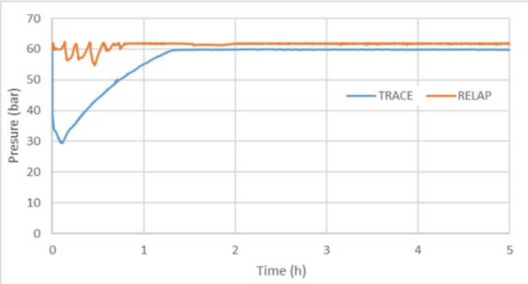

Figure 6. Pressure in SIRIO facility during simulation of steady state.

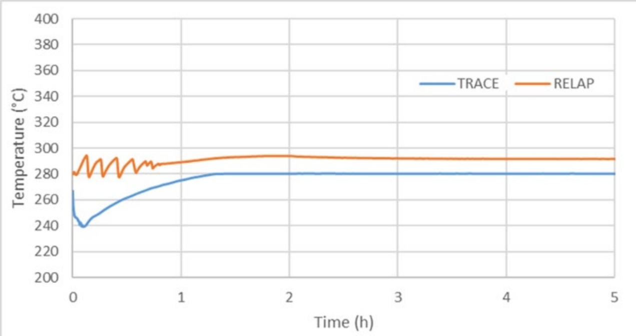

Figure 7. Salt temperature in heater during simulation of steady state.

The results of the simulations performed with the two codes, presented in Figure 8 (pressure) and Figure 9 (salt temperature) show notable differences. In particular, the pressure calculated with the TRACE code is about 15 bar higher than the pressure, calculated with the RELAP5 code. The corresponding temperature difference is about 20 °C. The pressure difference causes a different saturation temperature, which then influences the condensation rate. Nevertheless, results of both simulations appear sensible. This increases the confidence in the successful performance of the planned experiment, which was the essential purpose of the performed simulations.

7 CONCLUSIONS

Scaled-down conditions to perform an experiment on Passive Isolation Condenser (PIC) actuation during an accident in a Pressurized Water Reactor in the SIRIO experimental facility were defined. The planned experiment was simulated with the TRACE and RELAP5 codes. Despite some notable differences, simulation results obtained with the two codes show that the proposed experimental conditions are sensible, as the power provided by the mock steam generator is successfully removed and the transient gradually evolves towards a steady state, avoiding depressurization and over-cooling. Simulation results will be compared with results of the actual experiment that is to be performed in the autumn 2022.

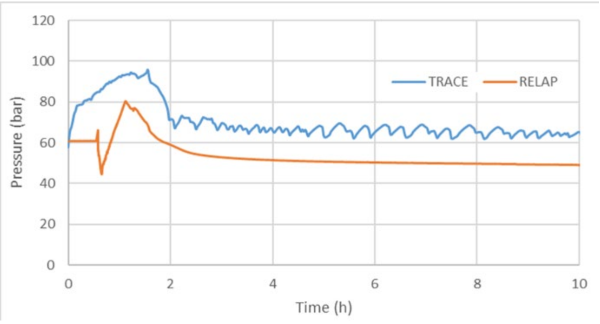

Figure 8. Pressure in SIRIO facility during simulation of transient.

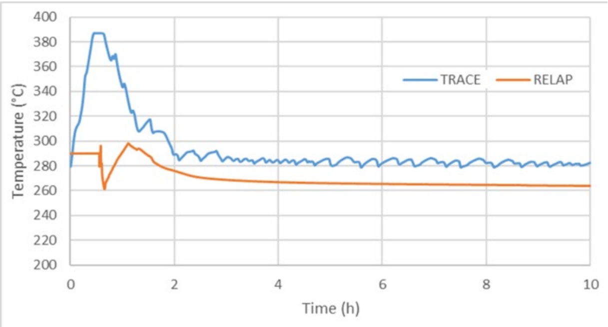

Figure 9. Salt temperature in heater during simulation of transient.

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